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A SHADOW BAND CONTROL SYSTEM FOR SUN TRACKING SOLAR COLLECTORS

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Division of
Mechanical Engineering

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A SHADOW BAND CONTROL SYSTEM FOR SUN TRACKING SOLAR COLLECTORS

DISPOSITIF DE COMMANDE À BANDE D'OMBRE POUR CAPTEURS DE POURSUITE DU SOLEIL

J. F. Lane

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ABSTRACT

The Low Temperature Laboratory of the Division of Mechanical Engineering, with support from the Federal Government's Interdepartmental Energy Research and Development Program and in collaboration with the National Research Council's Solar Energy Project, has established facilities aimed at developing advanced equipment for the collection of solar energy for industrial applications in a northern climate. During the establishment of these facilities a device for maintaining tracking solar collectors pointed at the sun was developed. This report outlines the experience gained during the development of the sun tracking control system and the principles of its operation.

The control system is based on the shadow band principle where an umbrella mounted on the side of the collector casts a shadow on two photocell solar sensors. The photocells are located on opposite sides of the umbrella and each is 50% shaded by the umbrella. As the sun moves across the sky the shadow moves off one sensor and onto the other, changing their relative resistances. The changes in resistance are sensed in a Wheatstone bridge circuit with a null sensing relay connected across its null points. These relays in turn operate the solar collector drive motors to correct its position.

Three basic circuits are described and the operating experience with each outlined.

This research was the basis for the construction of a control system for a two-axis tracking platform.

RÉSUMÉ

Le Laboratoire des basses températures de la Division de génie mécanique, avec l'aide du Programme interministériel de la recherche et du développement énergétiques du gouvernement fédéral, a établi, en collaboration avec le Projet "Énergie Solaire" du Conseil national de recherches, des installations destinées à la mise au point d'équipement perfectionné pour le captage d'énergie solaire en vue d'applications industrielles dans des conditions climatiques septentrionales. Pendant la phase d'établissement de ces installations, on a mis au point un dispositif permettant de maintenir les capteurs de poursuite pointés vers le soleil. Le présent rapport décrit l'expérience acquise pendant la mise au point du dispositif de commande de poursuite du soleil ainsi que les principes de son fonctionnement.

Le dispositif de commande est basé sur le principe de bande d'ombre: un parapluie fixé sur le côté du capteur projette une ombre sur deux détecteurs solaires à cellule photo-électrique. Les cellules sont placées in opposition, de façon que chacune soit à 50% couverte par l'ombre que projette le parapluie. A mesure que le soleil se déplace dans le ciel, l'ombre se déplace d'un détecteur vers l'autre, ce qui produit une modification de leurs résistances relatives. Les variations de résistance sont détectées par un circuit à pont de Wheatstone comprenant un relais à détection de zéro entre ses points d'équilibre. Ces relais commandent à leur tour les moteurs d'entraînement du capteur de façon à corriger sa position.

On décrit trois circuits de base ainsi que l'expérience pratique acquise avec chacun.

Cette recherche a servi de base à la fabrication d'un dispositif de commande pour une plate-forme de pursuite à deux axes.

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A SHADOW BAND CONTROL SYSTEM FOR SUN TRACKING SOLAR COLLECTORS

1.0 INTRODUCTION

The large increases in oil prices in recent years have sparked a renewed interest in alternative energy sources such as coal, wood, nuclear and solar. Solar energy is particularly attractive as it is free, non-polluting and available in varying amounts everywhere. Various devices such as flat plate collectors, parabolic troughs, parabolic dishes or heliostat power-towers have been developed to collect solar energy. Depending on the type of collector, solar energy can be obtained in heat form at temperatures from near ambient to 2000°C. To obtain solar energy at temperatures above ≈100°C some form of concentrating device such as the parabolic trough or parabolic dish is required. To be effective these devices must point directly at the sun and follow it as it progresses across the sky.

Several devices are available to control a solar tracking collector but perhaps the simplest of these is a shadow band device. In a shadow band device, some form of umbrella casts a shadow on a sensor. As the sun moves across the sky the movement of the shadow on the sensor is measured and corrective action taken to maintain the shadow centered on the sensor. The sensing device is usually a photoelectric cell. Often two photoelectric cells are used in opposition with the shadow moving off one cell and onto the second cell giving a manigified differential effect.

The Low Temperature Laboratory of the Division of Mechanical Engineering, when setting up a solar energy test facility [Ref. 1] with support from the Federal Government's Interdepartmental Energy Research and Development Program and in collaboration with the NRC Solar Energy Project, proceeded with the development of a shadow band controller which would be simple to assemble and could be made from readily available components. The remainder of this report will outline the steps taken to develop a shadow band controller suitable for use with a tracking solar collector.

2.0 BASIC CONTROL CIRCUIT

The basic concept consists of an umbrella casting a shadow on two photoelectric cells. The photocells are arranged so that each photocell is on opposite sides of the umbrella. As the sun moves across the sky the shadow of the umbrella moves off one photocell and onto the opposing one. The two photocells are part of a Wheatstone bridge circuit with a null sensing relay connected across the null points of the bridge. As the resistance of the photocells becomes unbalanced by the moving shadow, the bridge circuit becomes unbalanced and actuates the null sensing relay. It in turn actuates the collector drive motors to correct the solar collector's position.

The photocells can be of any type as long as they are not overloaded by the current passing through the Wheatstone bridge. Photocells of the type used to sense flames in boilers and readily available from local heating supply houses were used in this development.

The null sensing relay used initially was of the mechanical type, i.e. one where a relay coil caused an armature to actuate and known as a micropositioner. This type is not now readily available and was replaced with a solid state null sensing relay for use with the collector.

The control circuit [Fig. 1], used initially with the micropositioner, was built up in three levels. The lowest level was a 3-volt circuit which spanned the Wheatstone bridge containing the photocells and actuation coils of the null sensing relay. The second level was a 24-volt circuit which contained micropositioner contacts and the actuation coils of the relays controlling the forward and reverse operation of the tracker drive motors. The third level was a 110-volt circuit which provided power for the two lower control levels and the tracker drive motors.

The initial circuit was assembled in breadboard fashion and tested on a small polar axis type tracking unit [Fig. 2]. The system tracked the sun satisfactorily but had one major operational problem. When the differential voltage across the null points of the Wheatstone bridge circuit (level 1) was at the lower tripping threshold of the micropositioner, there was insufficient current through the coils to cause its contacts to close tightly. The result was a high resistance contact which would not pass sufficient current to pick up the motor control relays in the level 2 circuit. As a result the motor relays "chattered". This condition was unacceptable.

The circuit was revised as shown in Fig. 3 to provide more stable operation. The revisions consisted of installing two small reed relays across the output contacts of the micropositioner. The reed relays had 5-volt coils and would pick up at very low actuation currents. The relays, in turn, shorted out a small resistance in series with the Wheatstone bridge to increase the differential voltage across the bridge and draw the micropositioner contacts tightly together, giving the control circuit a hysteresis effect. In addition, the first and second levels were combined and operated on 24 VDC. A series resistor was installed in the Wheatstone bridge circuit to reduce its voltage to 8 VDC. These changes provided for a higher voltage across the Wheatstone bridge null points when required, and resulted in cleaner closing of the micropositioner relay contacts. Fig. 4 shows the breadboard assembly of this circuit.

The above changes totally eliminated "chattering" of the relay contacts except under very bright noonday sunlight conditions where "chattering" would develop for a fraction of a second.

3.0 OPERATING EXPERIENCE WITH MICROPOSITIONER RELAY

The normal running cycle consisted of a running or "on" time followed by an "off" time. The "on" time during a cycle could be controlled by adjusting the DC drive motor speed on the polar axis tracker. The speed adjustment available was from 20% to 100% of maximum speed.

The ability of the tracking system to follow the sun was measured by a transducer developed for that purpose. In principle, the transducer measures the position of a shadow cast by the sun relative to the zero tracking error location on a shadow plane. The measurement is performed by an inexpensive silicon solar cell mounted on the shadow plane such that at zero tracking error half of the cell is in shadow and half in sunlight. A hood surrounds the cell to reduce the impingement of indirect solar radiation on the solar cell. The output of the solar cell is measured as an indication of the distance between the shadow line and the zero error reference line.

A typical tracking error trace of the micropositioner actuated shadow band control system is shown in Fig. 5. There is some variation in the length of the period from cycle to cycle. The variation in Fig.5 is from 17 seconds to 173 seconds with an average period of 64 seconds. The corresponding tracking error is from +.54° to -0.24°. The erratic behaviour of the tracking system is due to mechanical friction and variable contact resistance in the micropositioner relay.

It should be noted in Fig. 5 that the tracker "on" times are very short. The "on" times could be increased by reducing the speed of the drive motor. A significant increase in the "on" time will reduce the cycling of the drive motor and may even be eliminated by adjusting the drive motor speed to match the sun speed if a polar axis tracker is being used, as was done with the tests of the micropositioner relay. When a tracker is capable of running at or near sun speed, a second higher speed drive must be included so that the collector can be positioned facing the sun before the sun speed is selected.

During cloudy periods when the umbrella does not cast any shadow on the photocells, the tracker control system does not activate and the controls have no sense of where the sun is. In some instances when the sun is not shining but there is a bright cloud in the sky which is capable of casting a slight shadow on the sensors, the system will lock onto the cloud and track to it. The system will return to tracking the sun whenever it emerges. It is evident that during cloudy periods the shadow band controller requires some form of auxiliary control such as a computer or microprocessor to maintain the solar platform oriented towards the sun.

4.0 SOLID STATE NULL SENSING RELAY CONTROL CIRCUIT

The micropositioner used in the early development was not available commercially and therefore the circuit was revised to accept a solid state null sensing relay which was available. This system was used to control a two-axis tracking platform with a 3-metre parabolic dish solar collector. The revised circuit for a single axis of control is shown in Fig. 6. This circuit is essentially a three-level circuit operating entirely on AC current to suit the solid state relay. The first level operates at 6 VAC and contains the Wheatstone bridge circuit. The second level operates at 24 VAC and contains the control relays for the drive motors. The third level operates at 110 VAC and provides power for levels 1 and 2 and the solar tracker drive motors. The actual drive motors are variable speed DC motors.

The null sensing solid state relay had the following input characteristics:

(i)	Nominal input circuit impedance	20K ohms
(ii)	Min. pull-in signal	5 RMS millivolts
(iii)	Max. signal overvoltage	10 RMS volts
(iv)	Operating voltage range ratio	2000:1
(v)	Pull in/drop out differential (nominal)	10%

The low pull in signal voltage (5 millivolts) permitted the construction of a very sensitive control system. The small pull in/drop out differential voltage (≈0.5 millivolts) accentuated the sensitivity and it was necessary to install a hysteresis circuit controlled by mini relays in the Wheatstone bridge circuit. The relays are shown in the circuit diagram [Fig. 6].

5.0 OPERATING EXPERIENCE WITH SOLID STATE NULL SENSING RELAY

The operating experience with the solid state null sensing relay was quite similar to that with the micropositioner. The increased sensitivity of the null sensing relay shortened the cycle period to about 10 seconds without the hysteresis loop in the Wheatstone bridge. A 10-second cycle period represents a sun movement of 2.5 minutes of arc. With the solar tracking system adjusted to maintain the positioning error equally spaced about the normal to the sun, the actual tracking error is less than ± 1.3 minutes of arc. The short cycle period places considerable strain on the operating components and motors as they are continuously starting and stopping. The addition of the hysteresis loop permitted the cycle period to be adjusted. For operation with NRC's two-axis tracker the hysteresis loop was adjusted to give a 5-millivolt shift in voltage across the Wheatstone bridge. This shift was established so that the differential voltage on the Wheatstone bridge will be close to zero when the null sensing relay turns "off".

A typical tracking error trace of the azimuth drive on the 3-metre dish tracker is shown in Fig. 7. The average period of the operating cycle is 21 seconds and the total error from peak to peak is 0.18°. The corresponding operating accuracy is ± 0.09°. The tracking error trace shown in Fig. 7 is biased to one side, as the instrument was not adjusted to give equal excursions on either side of the zero line before the trace was taken.

A typical tracking error trace of the elevation drive on the 3-metre dish tracker is shown in Fig. 8. The average period of the operating cycle is 67 seconds and the total error from peak to peak is 0.21°. The corresponding operating accuracy is ± 0.1°. Again, the tracking error trace is biased to one side, as the instrument was not adjusted to give equal excursions on either side of the zero line before the trace was taken.

The increased sensitivity accentuated the tendency of the system to choose bright clouds or light spots in an overcast sky. To alleviate this problem the tracker system is transferred to computer

control when the direct solar insolation level drops below 200 watts/sq. metre.

The "on" time with both the azimuth and elevation drive is very short. The short cycle period could be improved by reducing the speed of both the azimuth and elevation drive motors to more nearly match the sun speed. Under these circumstances a two-speed system would be required, a slow speed for solar tracking and a fast speed for rapid positioning of the collector before reverting to tracking mode.

Fig. 9 shows the umbrella shade and photocell mount used with the two-axis solar tracker with a parabolic dish.

Fig. 10 shows the complete control system for the two-axis tracker. The Wheatstone bridge and the hysteresis circuit are mounted on the fibreglass board at the bottom of the control panel.

The system has been in operation for about 18 months during which time one photocell has failed. The photocells used are not designed for outdoor use and the failure was attributed to moisture reaching the connections at the rear of the sensor. Some form of weather protector is recommended for the outdoor sensor units.

6.0 CONCLUSIONS

The shadow band tracking sensor is a very accurate method of controlling a tracking type solar collector. It is easily capable of controlling the tracker to within 5 minutes of arc.

On cloudy or overcast days the tracker control either does not actuate or will track onto a bright spot in the overcast sky. Under these conditions some alternate form of control must be used to maintain the solar tracker pointed at the sun.

The system can be built from commercially available components. An expert knowledge of electronics is not required to assemble it.

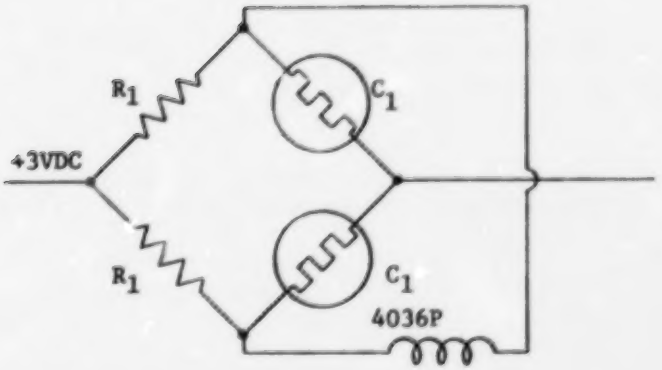
Weather protection is required for the photocell sensor units.

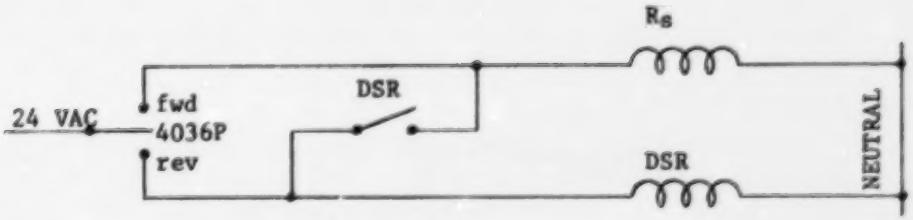
7.0 REFERENCE

Lane, J.F.
Beldam, R. P.
"Research Facilities at NRC for Producing Solar Industrial Heat"
Proceedings of "Energex '82" Conference, Solar Energy Society of Canada Inc., University of Regina, Regina, Saskatchewan, 23-29 Aug. 1982, Vol. II, p.703-708.

LEGEND

R_1	110 Ω
C_1	PHOTOCELL
4036P	MICROPOSITIONER
R_s	RUN-STOP RELAY
DSR	DIRECTION SELECTOR RELAY





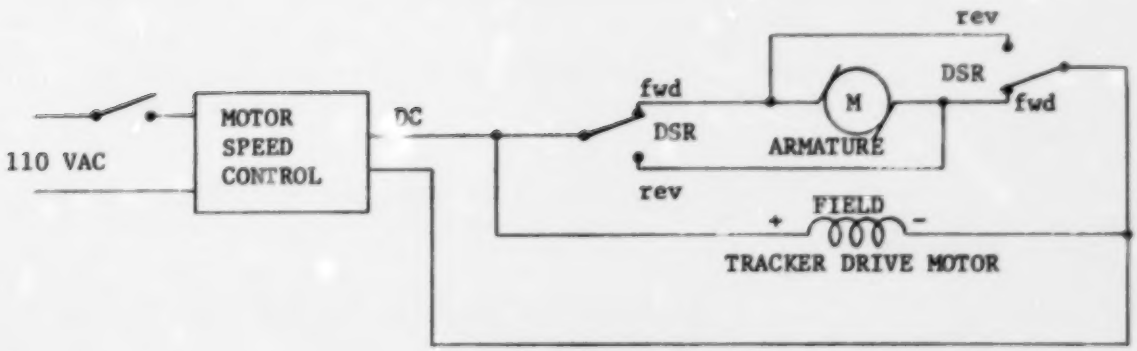


Fig. 1 Basic three level shadow band control circuit

Fig. 2 Polar axis solar tracking platform

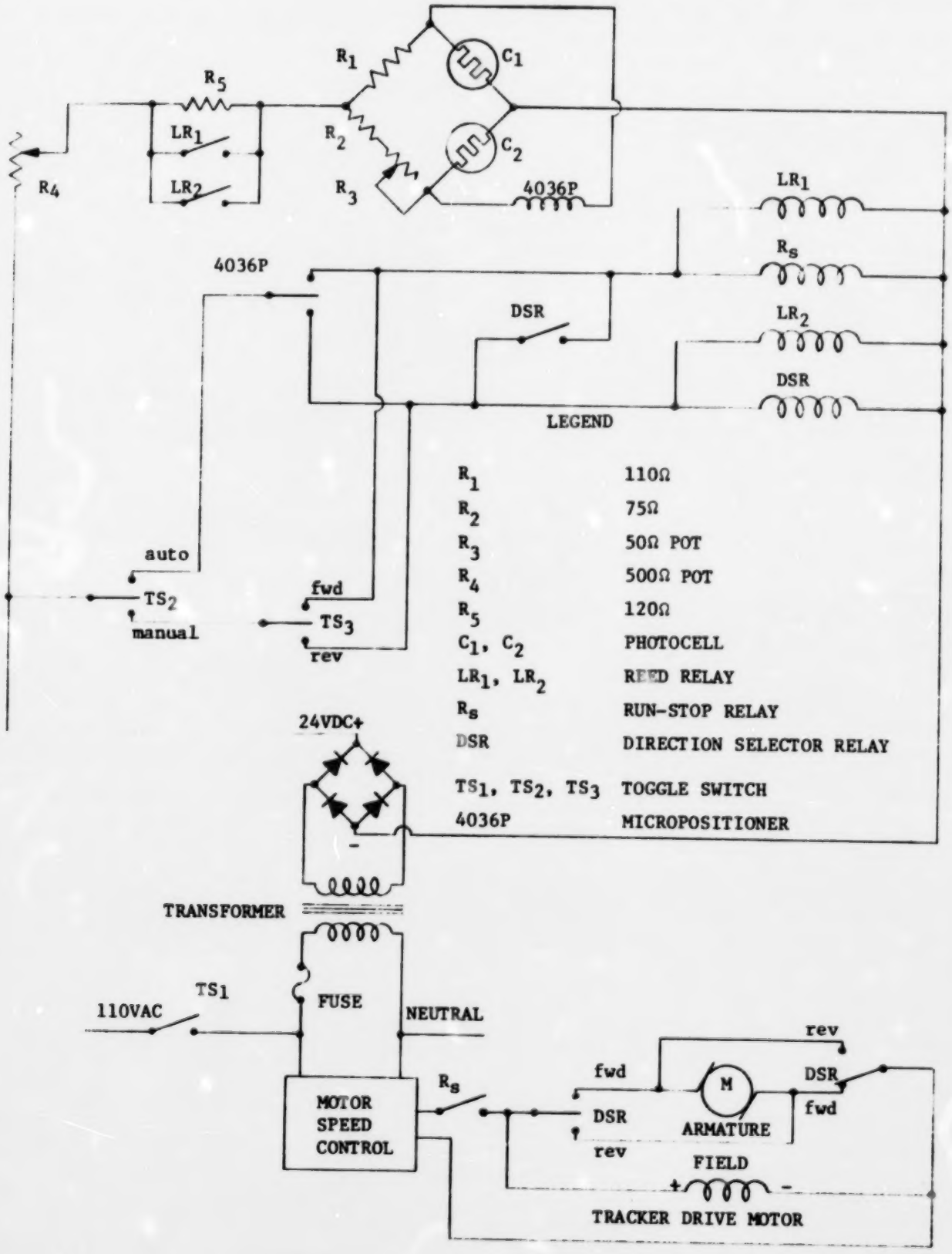


Fig. 3 Revised controller circuit with micropositioner

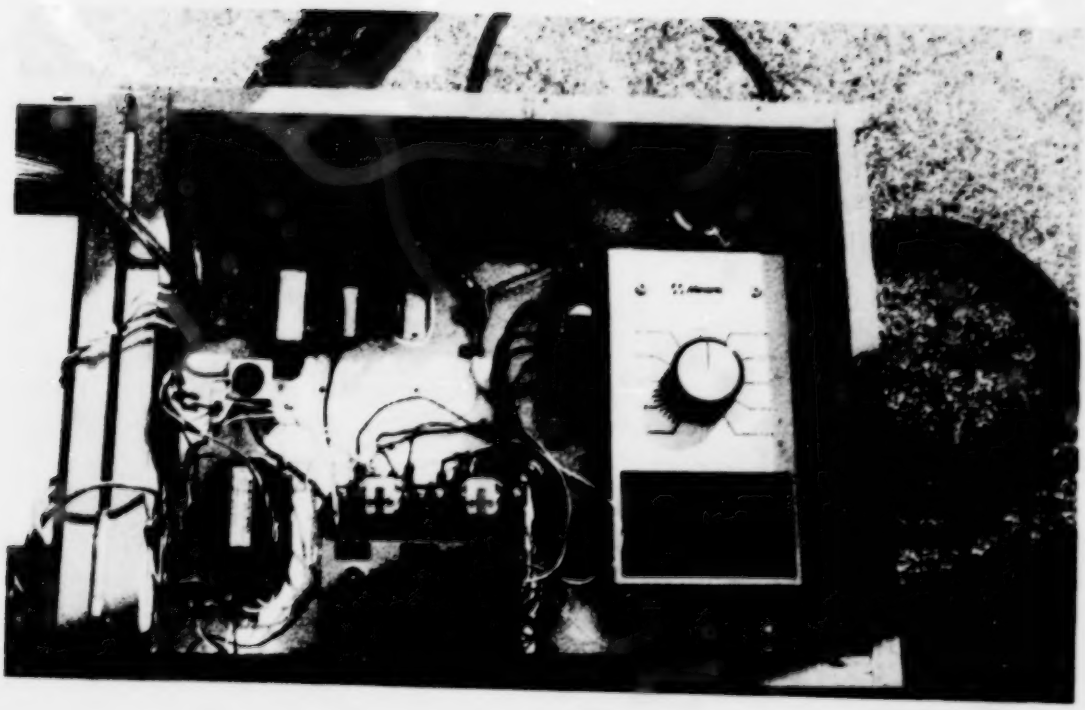


Fig. 4 Shadow band control circuit breadboard assembly

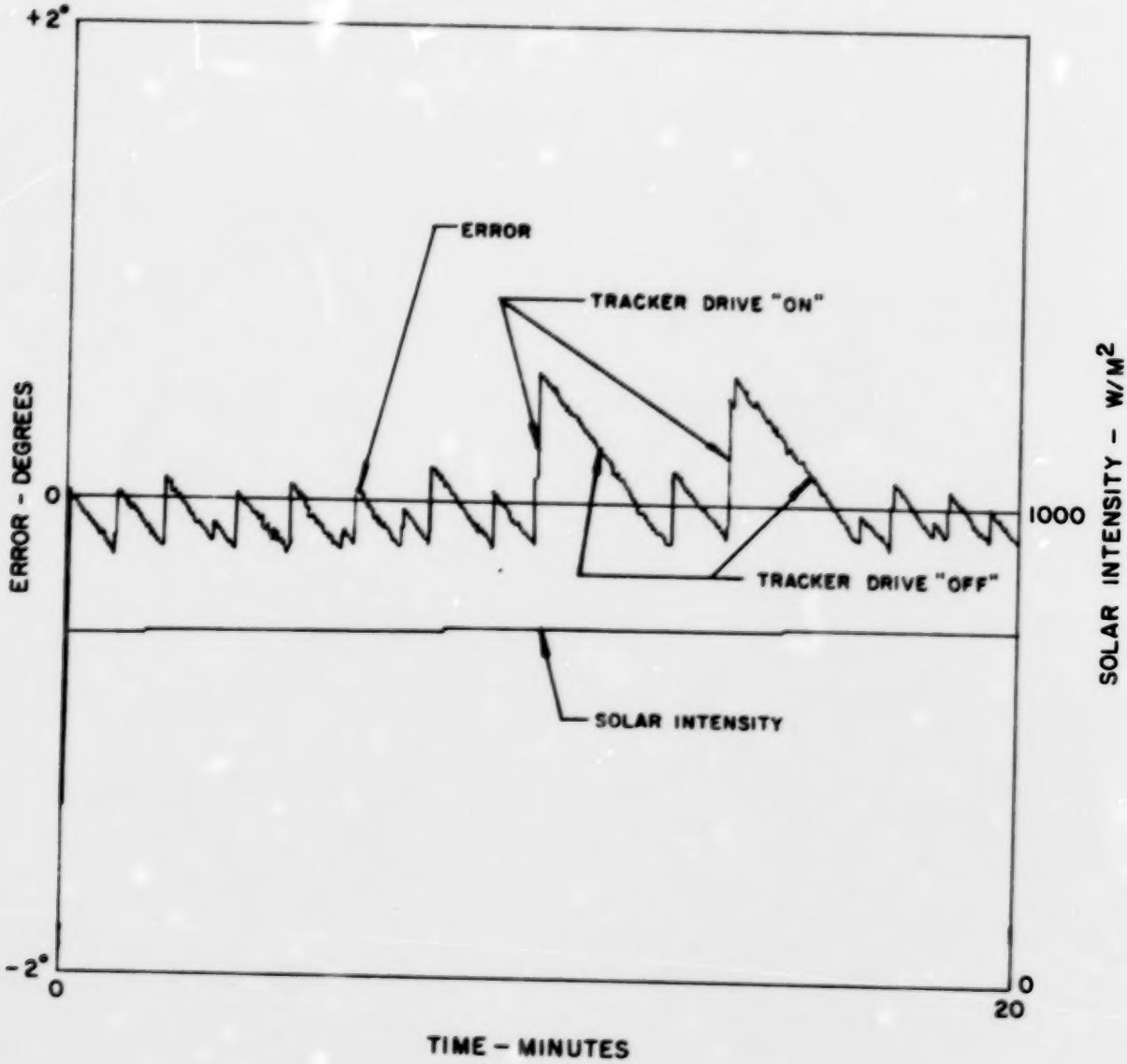


Fig. 5 Tracking error of micropositioner actuated shadow band control

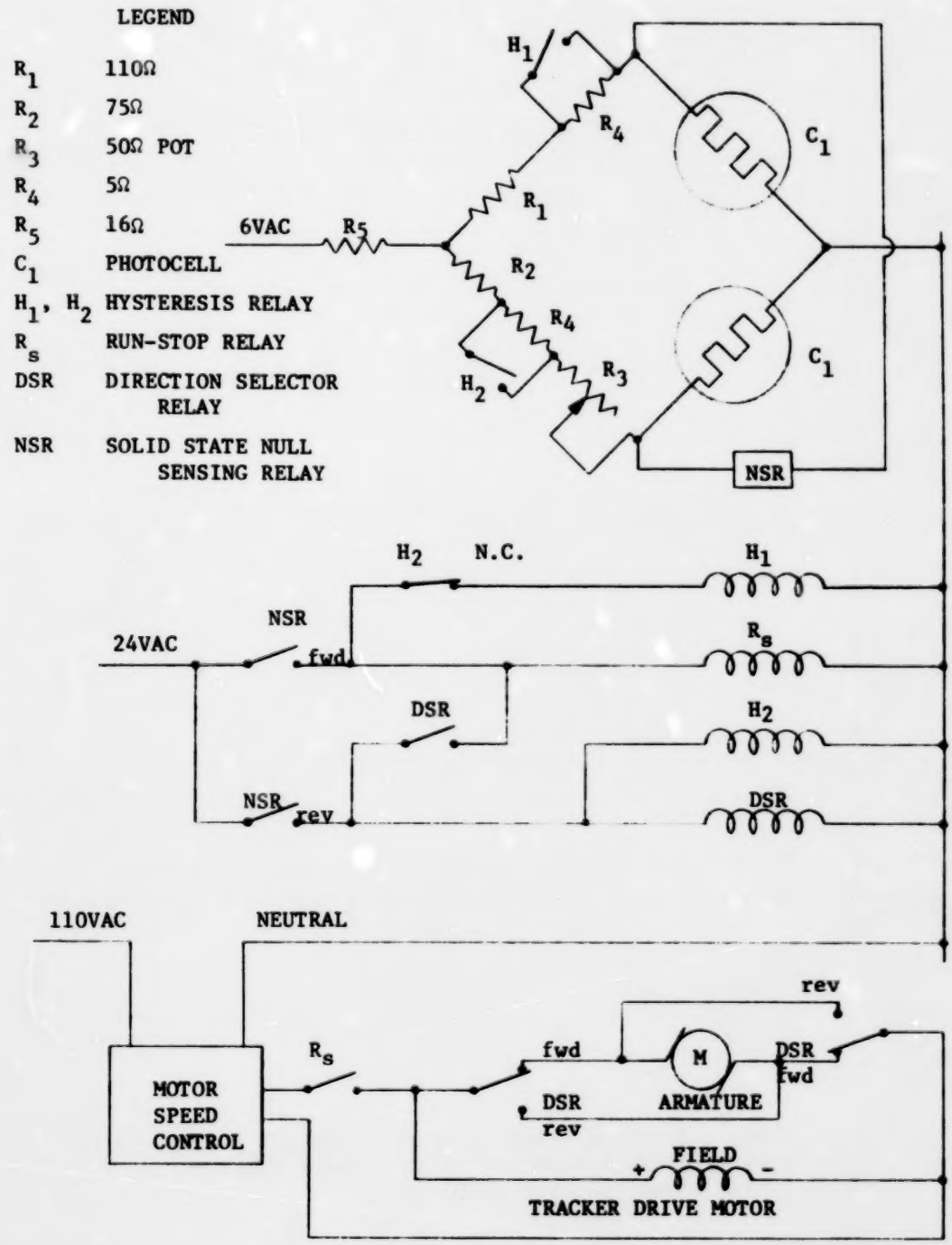


Fig. 6 Shadow band collector control with solid state null sensing relay

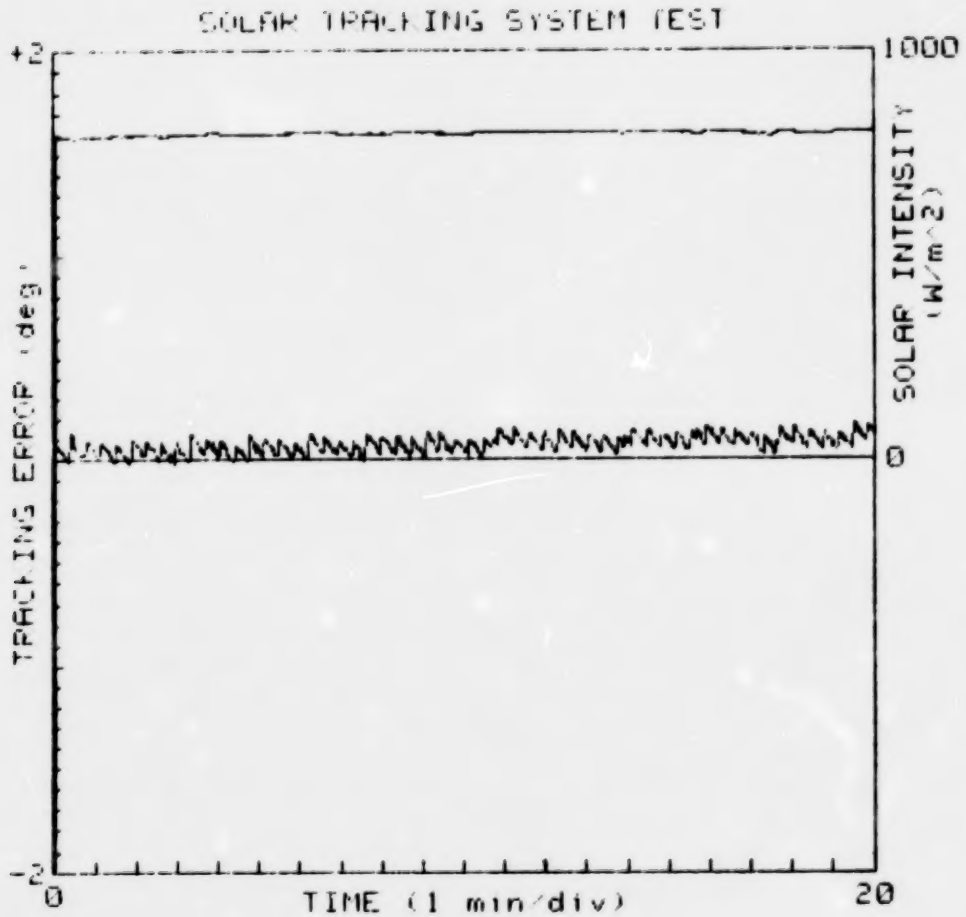


Fig. 7 Typical tracking error trace with the solid state null sensing relay system controlling the azimuth drive of a two-axis sun tracking platform

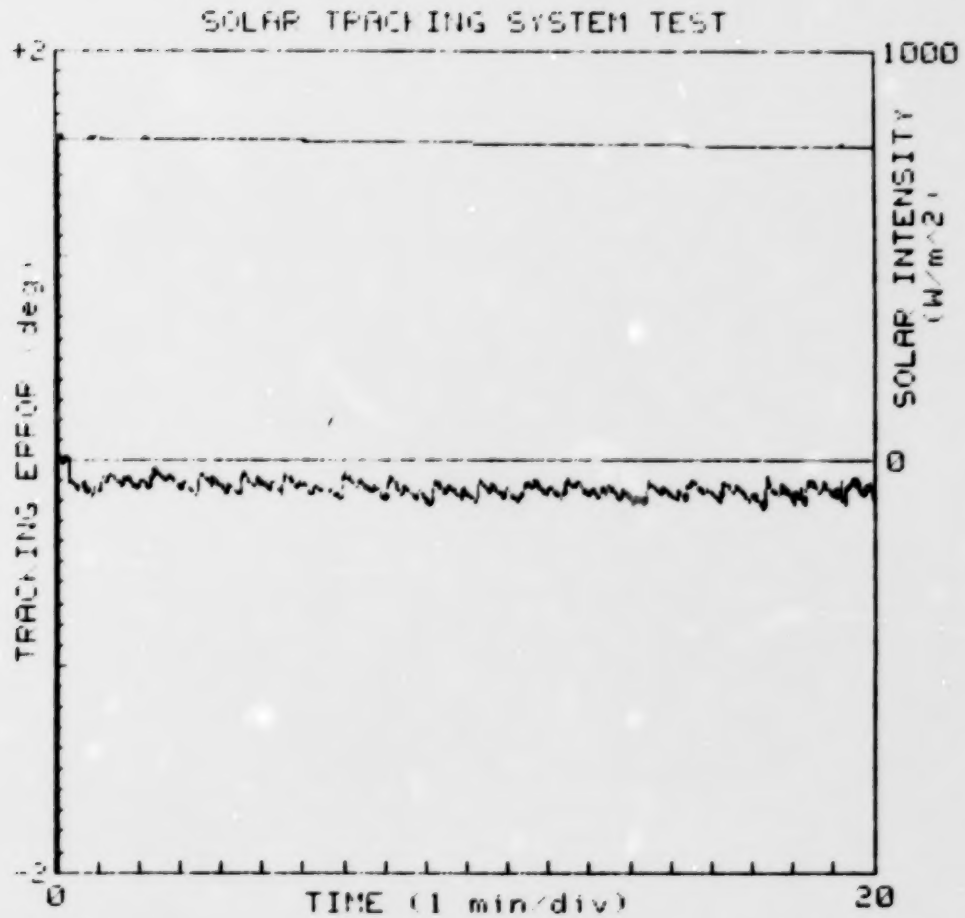


Fig. 8 Typical tracking error trace with the solid state null sensing relay system controlling the elevation drive of a two-axis sun tracking platform

Fig. 9 Umbrella solar sensor unit

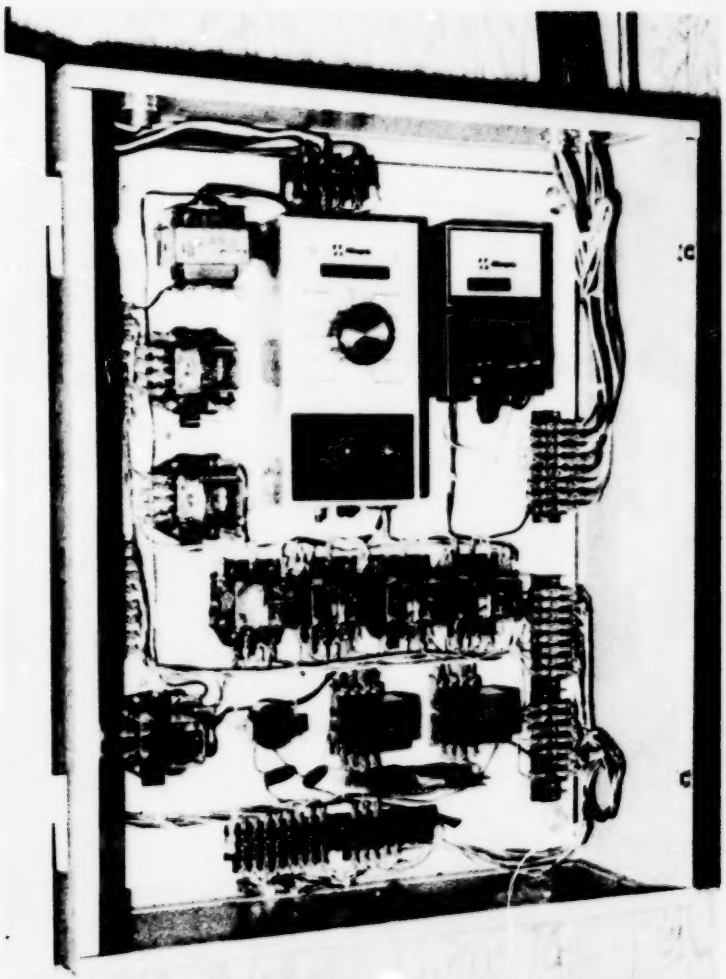


Fig. 10 Control panel for a two-axis tracking platform

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DESCRIPTORS(KEY WORDS)/MOTS-CLÉS (14)

Solar Energy; Control; Solar Collectors

SUMMARY/SOMMAIRE (15)

This report describes three circuits developed during the establishment of a solar energy concentrating solar collector test system and outlines the operating experience obtained with each circuit.

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